



Transient Burning Rate Model of Solid Propellant in Electrothermal-Chemical Launch

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Theory

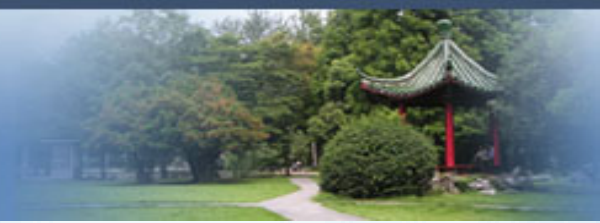
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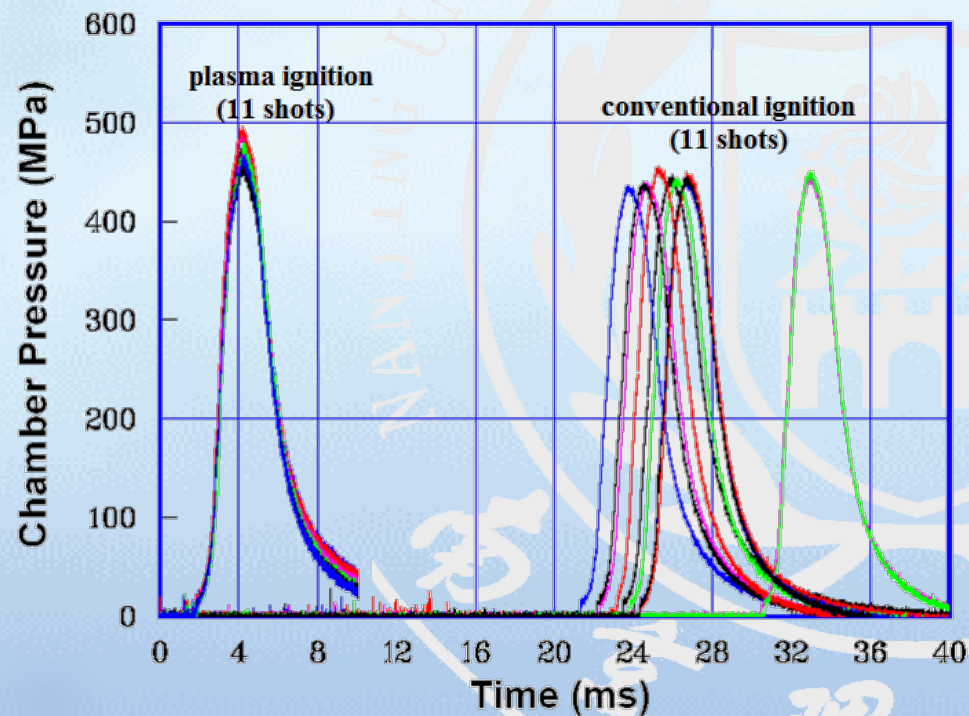
Conclusions

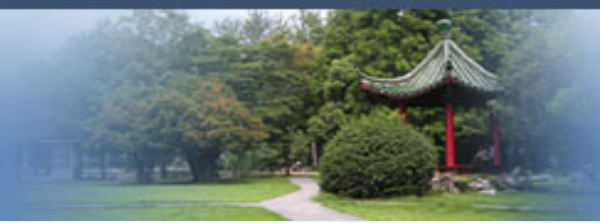




1 Introduction

- ❖ Reduce the ignition delay time
- Improve the ignition uniformity





1 Introduction

❖ Control the pressure

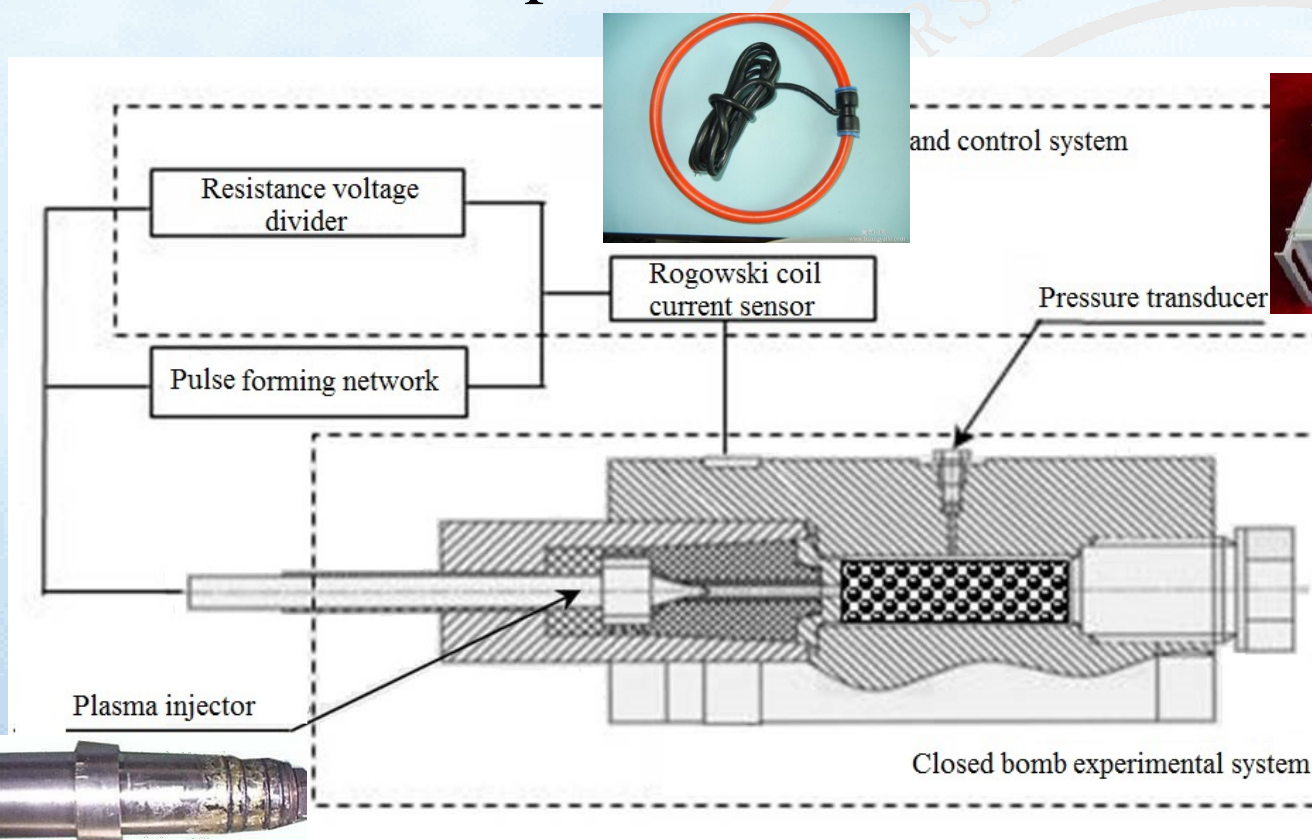
Improve the projectile muzzle kinetic energy



❖ 4/7 high-nitrogen solid propellant

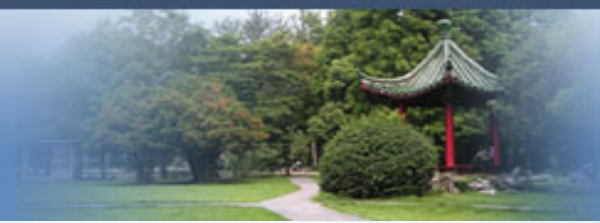
2 Experiments

2.1 Closed bomb experiments



and control system





2 Experiments

2.1 Closed bomb experiments

The closed bomb volume is 356cm^3 .

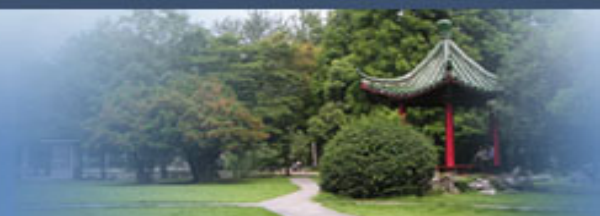
The loading density is 0.249g/cm^3 .

No.	ignition	U_0/kV
1	conventional	-
2	conventional	-
3	plasma	8.3
4	plasma	10
5	plasma	10.1

Test No.3 and No.4
at the center of the closed bomb

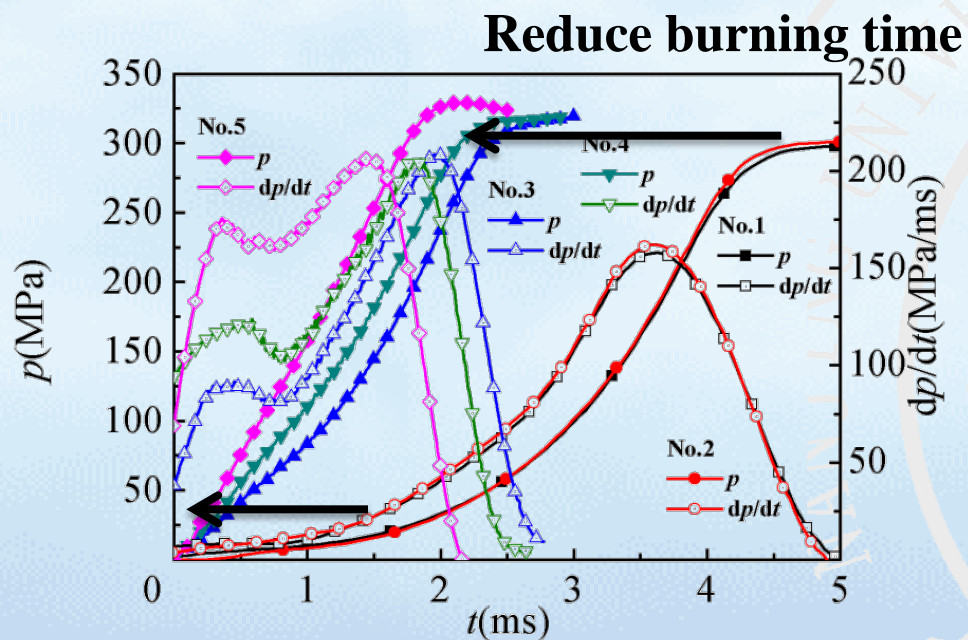
Test No.5
at the exit of the plasma generator





2 Experiments

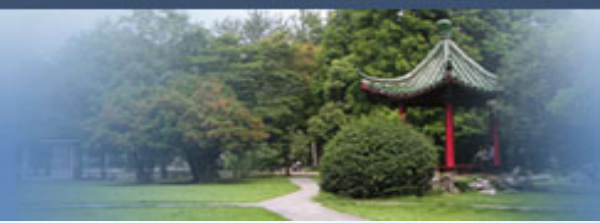
2.1 Closed bomb experiments



Improve the pressure

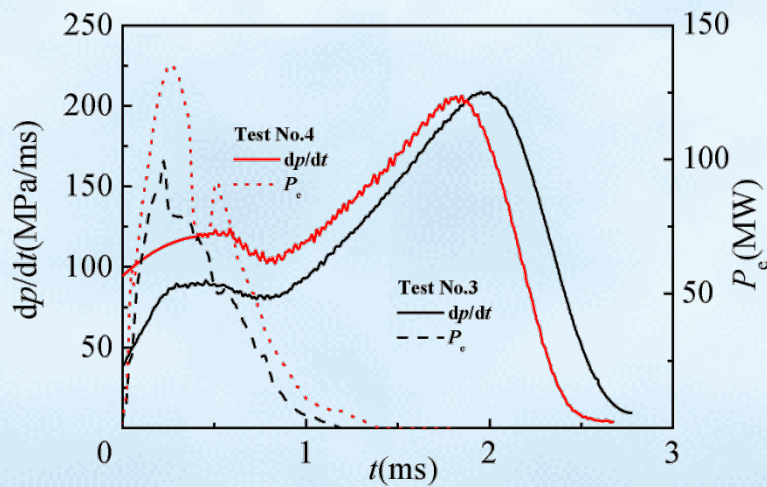
No.	t_{ig}/ms	t_{end}/ms	p_{m}/MPa
1	1.604	5.05	298
2	1.673	4.95	300
3	0.261	2.93	318
4	0.197	2.44	319
5	0.167	2.16	329

Reduce ignition time

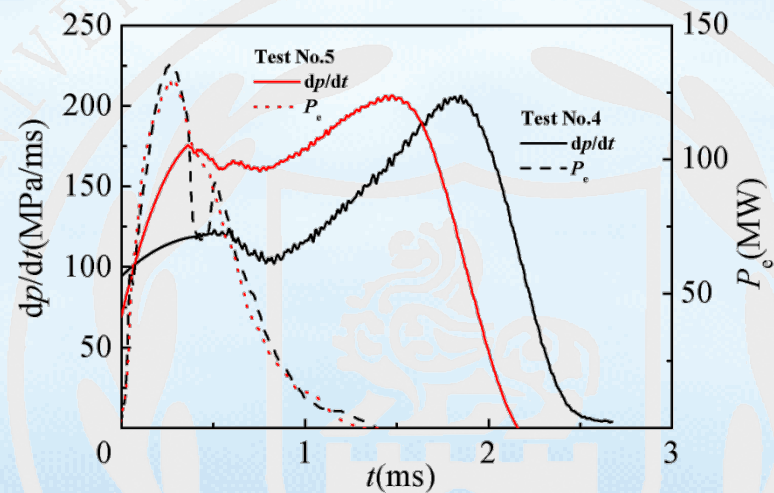


2 Experiments

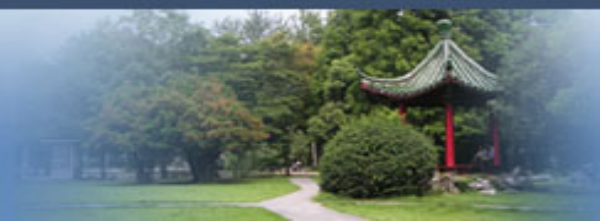
2.1 Closed bomb experiments



$$dp / dt \propto P_e$$



$$dp / dt \propto 1 / \Delta L$$

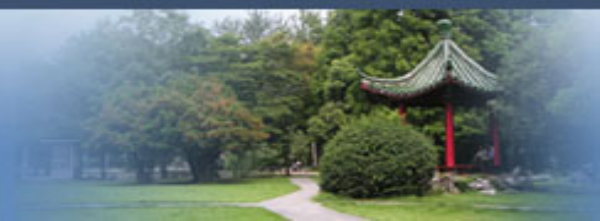


2 Experiments

2.2 ETC launch experiments



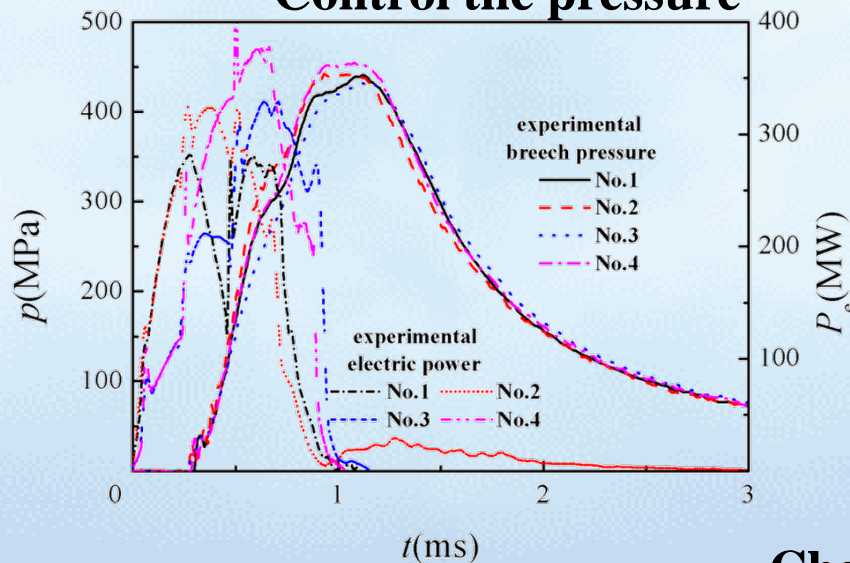
No.	$t/\mu\text{s}$	U_0/kV
1	0, 0, 470, 470	9.448, 9.364, 9.59, 9.938
2	0, 0, 250, 500	9.326, 9.281, 10.029, 9.979
3	0, 250, 500, 500	9.497, 9.378, 10.184, 10.498
4	0, 250, 250, 500	9.392, 9.942, 9.805, 8.775



2 Experiments

2.2 ETC launch experiments

Control the pressure

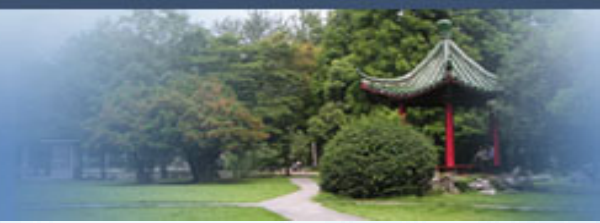


Improve the projectile muzzle velocity

No.	E_{pl}/kJ	p_m/MPa	$v_{proj}/\text{m}\cdot\text{s}^{-1}$
1	191.6	441	2085
2	182.4	446	2086
3	200.4	438	2088
4	220.6	452	2123

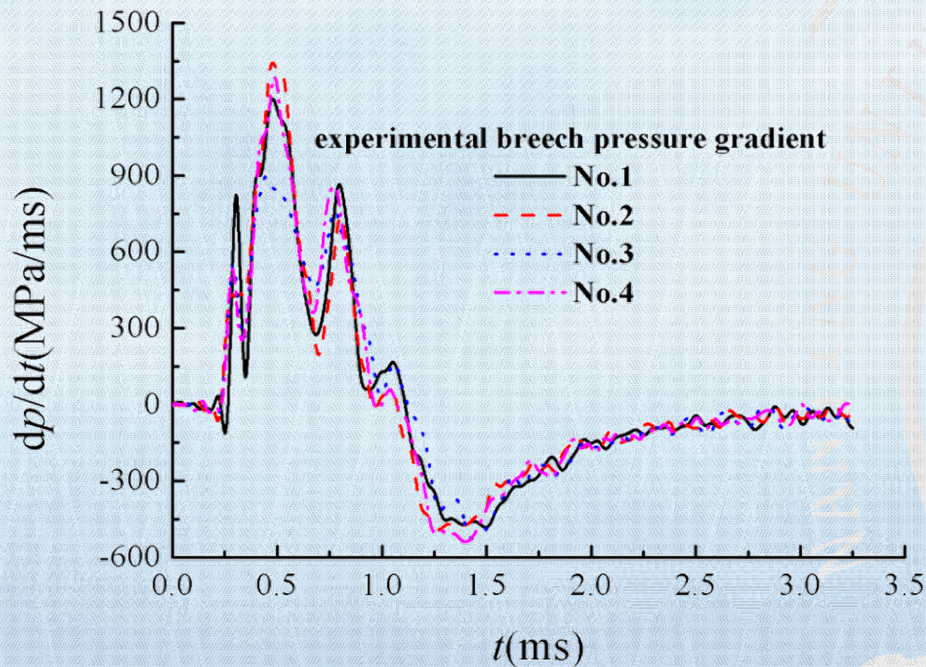
Change the input electrical energy





2 Experiments

2.2 ETC launch experiments



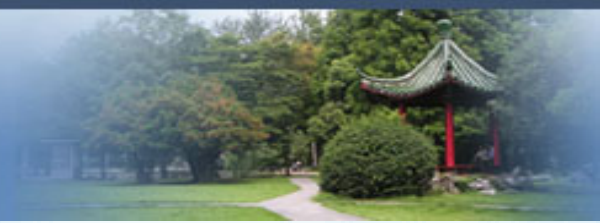
Influencing factors:

plasma

propellant burning progress

projectile motion





3 Theory

3.1 Closed bomb model

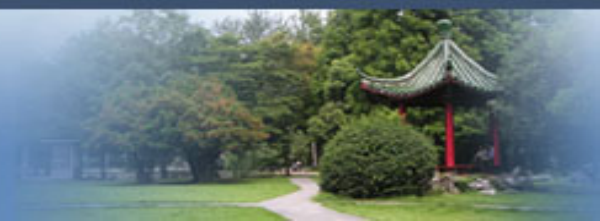
The gas phase state equation

$$p \left[V_0 - \frac{m}{\rho_p} (1 - \psi(t)) - \alpha m \psi(t) - \alpha_{ig} m_{ig}(t) \right] = T (R m \psi(t) + R_{ig} m_{ig}(t))$$

Energy conservation equation

$$(1 - c_1) f m \psi(t) + f_{ig} m_{ig}(t) + (k - 1) c_{pl} E_{pl}(t) = T (R m \psi(t) + R_{ig} m_{ig}(t))$$





3 Theory

3.2 0D internal ballistics model

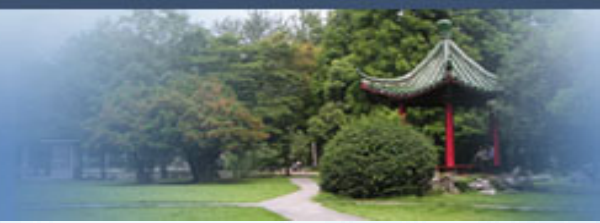
$$\psi = \begin{cases} \chi Z(1 + \lambda Z + \mu Z^2) & (Z < 1) \\ \chi_s Z(1 + \lambda_s Z) & (1 \leq Z < Z_b) \\ 1 & (Z \geq Z_b) \end{cases}$$

$$v = \frac{dl}{dt}$$

$$Sp = \varphi m \frac{dv}{dt}$$

$$p[V + V_0 - \frac{\omega}{\rho_p}(1 - \psi) - \alpha \omega \psi] = f \omega \psi - \frac{\theta \varphi m v^2}{2} + \theta E_{pl}$$





3 Theory

3.3 Burning rate law

$$u = u_1 p^{n_1}$$

Plasma P_e

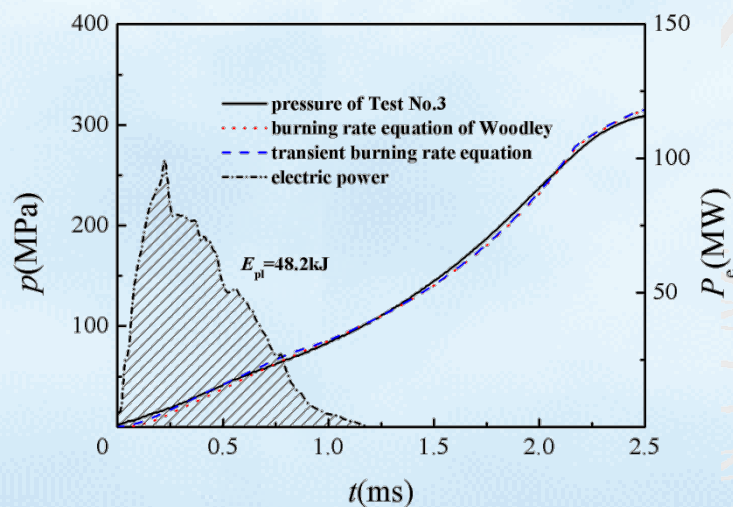
$$u = u_1 p^{n_1} (1 + \beta_e P_e)$$

dp/dt

$$u = u_1 p^{n_1} \left(1 + \frac{\alpha(t) n_1}{u_1^2 p^{2n_1+1}} \frac{dp}{dt} \right) (1 + \beta_e P_e)$$

4 Simulations

4.1 Closed bomb simulations



$$\beta_e = 0.005\text{MW}^{-1}$$

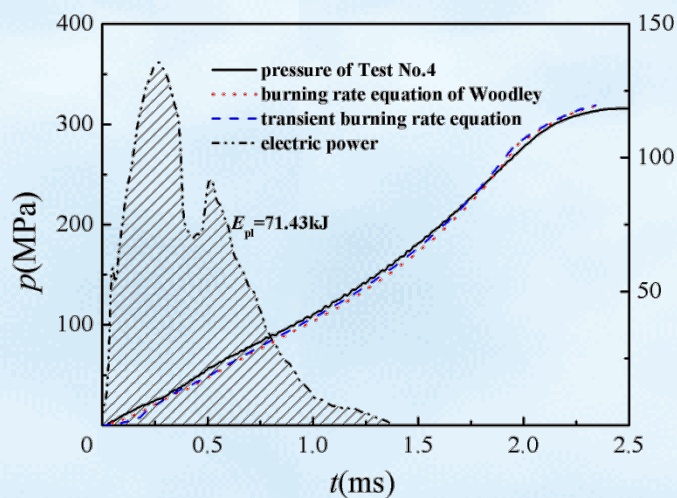
$$\sigma = \sqrt{\frac{\sum_{i=1}^n (p_{sim}(i) - p_{test}(i))^2}{n}}$$

$$\sigma_{Woodley} = 4.325\text{MPa}$$

$$\sigma_{transient} = 4.294\text{MPa}$$

4 Simulations

4.1 Closed bomb simulations

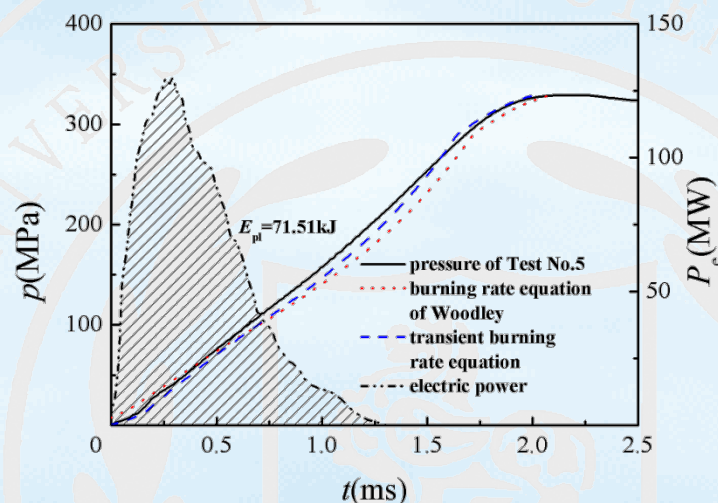


$$\sigma_{\text{Woodley}} = 9.312 \text{ MPa}$$

$$\sigma_{\text{transient}} = 4.91 \text{ MPa}$$

dp/dt

at the beginning of the ignition
after the electrical discharge

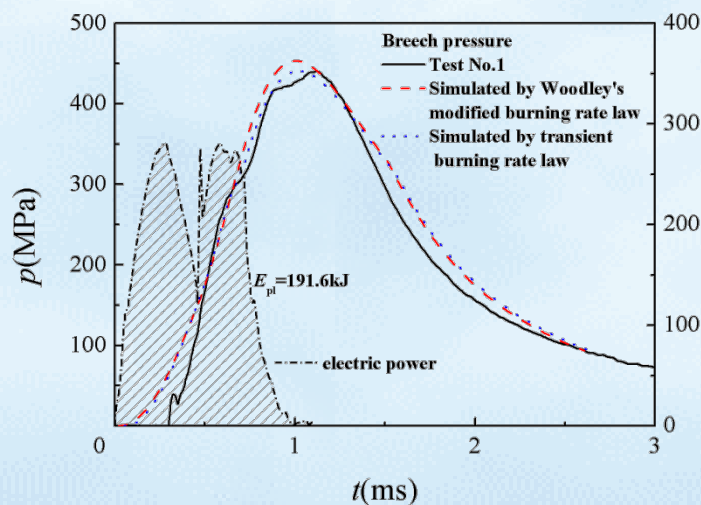


$$\sigma_{\text{Woodley}} = 13.506 \text{ MPa}$$

$$\sigma_{\text{transient}} = 5.715 \text{ MPa}$$

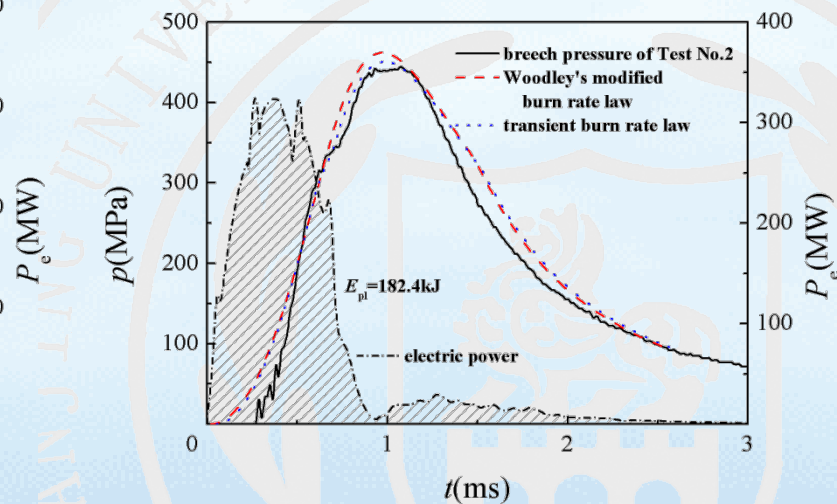
4 Simulations

4.2 ETC launch simulations



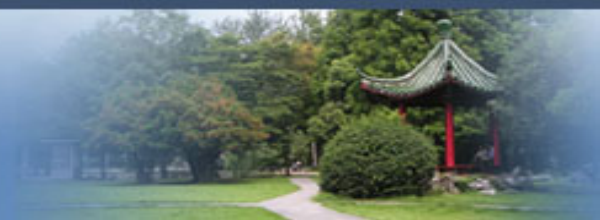
$$\sigma_{\text{Woodley}} = 25.47 \text{ MPa}$$

$$\sigma_{\text{transient}} = 23.87 \text{ MPa}$$



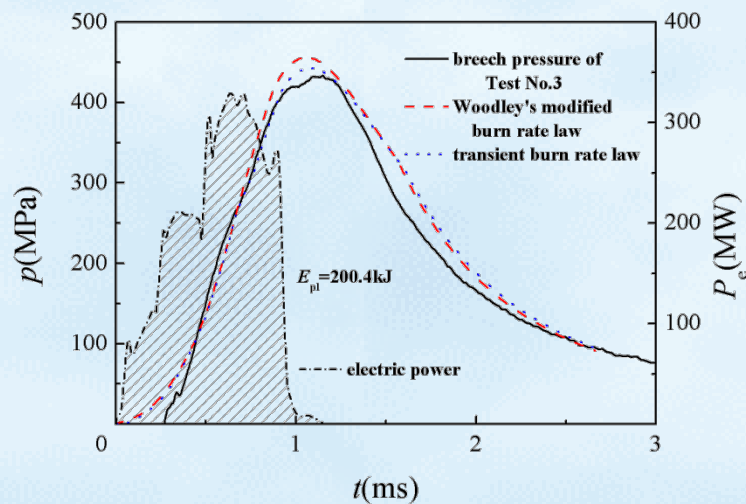
$$\sigma_{\text{Woodley}} = 25.75 \text{ MPa}$$

$$\sigma_{\text{transient}} = 24.01 \text{ MPa}$$



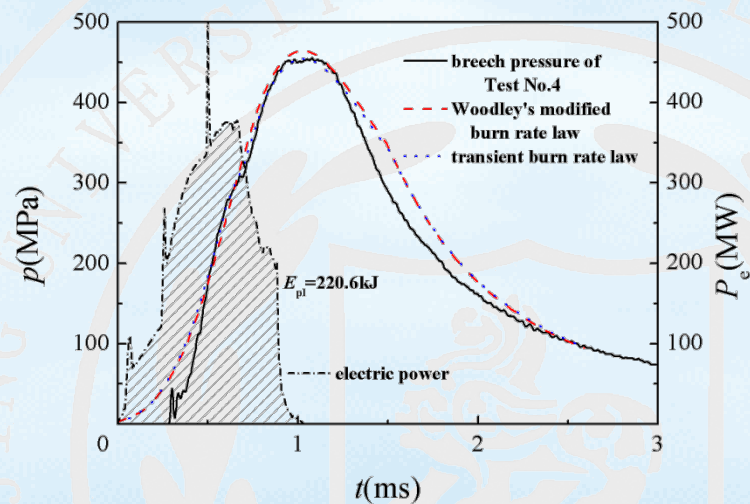
4 Simulations

4.2 ETC launch simulations



$$\sigma_{\text{Woodley}} = 24.44 \text{ MPa}$$

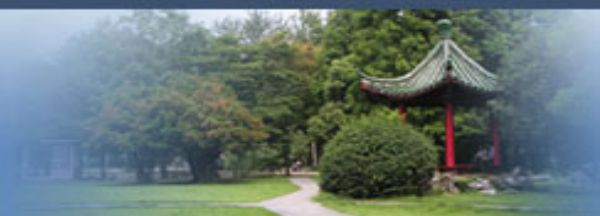
$$\sigma_{\text{transient}} = 22.01 \text{ MPa}$$



$$\sigma_{\text{Woodley}} = 25.16 \text{ MPa}$$

$$\sigma_{\text{transient}} = 24.71 \text{ MPa}$$

$$\sigma_{\text{transient}} < \sigma_{\text{Woodley}}$$



4 Simulations

4.2 ETC launch simulations

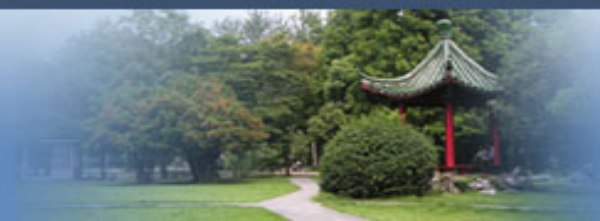
The pulse current duration is about 1ms.

No.	MSE(Woodley) within 1.2ms/MPa	MSE (transient) within 1.2ms/MPa	v_{proj} (Woodley)/ m/s (relative error)	v_{proj} (transient)/ m/s (relative error)
1	30.09	23.06	2104(0.91%)	2092(0.34%)
2	29.11	23.61	2111(1.20%)	2099(0.62%)
3	22.03	15.46	2099(0.53%)	2091(0.14%)
4	22.88	20.55	2137(0.66%)	2126(0.14%)

$\sigma_{Woodley}$ decreases only slightly or increases

$\sigma_{transient}$ decreases





5 Conclusions

- ❖ The pressure gradient changes rapidly with plasma.
- ❖ During the ignition time, the pressure gradient can be another important factor to analyze the influence of the plasma.
- ❖ The simulation accuracy can be improved by transient burning rate with EGGR coefficient and pressure gradient.





Thank you!

